Effect of Quenching Temperature on the Mechanical Properties of Cast Ti-6Al-4V Alloy

Reham Reda*1, Adel A. Nofal 2, Abdel-Hamid A. Hussein3

1-2Central Metallurgical R&D Institute, P.O.Box 87, Helwan, Egypt, 3Metallurgical Engineering Department, Faculty of Engineering, Cairo University, Giza, Egypt

*1metallurgist_reham@yahoo.com; 2adelnofal@hotmail.com; 3aahussein41@yahoo.com

Abstract

Ti-6Al-4V alloy is a workhorse of titanium industry; it accounts for about 60 percent of the total titanium alloy production. The high cost of titanium makes net shape manufacturing routes very attractive. Casting is a near net shape manufacturing route that offers significant cost advantages over forgings or complicated machined parts. However, the disadvantage of the as-cast titanium alloys, like other cast metals, is that the heat treatment remains only a limited option for improvement of their properties. The objective of this work was to study the effect of water quenching on mechanical properties of cast Ti-6Al-4V alloy. Tensile, hardness and charpy impact toughness tests were performed. The results showed that the final properties of cast Ti-6Al-4V alloy are highly dependent on the quenching temperature.

Keywords

Heat treatment; Cast Ti-6Al-4V alloy; Tensile properties; Hardness; Impact toughness; Fracture surface

Introduction

Titanium and its alloys have very attractive properties, e.g. high strength to weight ratio and excellent corrosion resistance, which enable them to be used in the fields of aerospace, biomedical, automotive, marine and military. [1-7]. The demand for the use of titanium and its alloys in many areas of applications has increased over the past years by the necessity for weight reductions that enhance the efficiency and greatly reduce the fuel consumption when used in the transportation systems, e.g. aerospace and automotive applications. [2,7].

The excellent corrosion resistance and biocompatibility make Ti and its alloys a material of choice compared with other metallic implant materials. [4-6,8]. In addition to applications of titanium in healthcare instruments such as wheelchairs, equipment for handicapped persons such as artificial limbs and artificial legs are currently making use of the unique properties of titanium alloys.

Due to high cost of titanium, the use of net-shape or near-net-shape technologies receives, an increasing interest considering the large cost saving potential of this technology in manufacturing parts of complex shapes, [2-5] such as cast frames for aircraft engines, compressor casings, cast fan frames, exhaust gas pipes of auxiliary gas turbines, connecting rod, intake and outlet valves and rim screws. [3-5]. Titanium castings have been used also in biomedical and dental applications, e.g. cast hip joint stems as well as for crowns and bridges. [4,5,8].

The possibilities to optimize the properties of cast parts, via the microstructural control, are limited to purely heat treatments, contrary to wrought material. For many alloys, the mechanical properties of castings are inherently lower than those of wrought alloys. Nevertheless, heat treatment of titanium castings yields mechanical properties comparable, and often superior, to those of wrought products. [2,4,5].

Ti-6Al-4V alloy has an excellent combination of strength, toughness and good corrosion resistance and finds uses in aerospace applications, pressure vessels, aircraft-turbine and compressor blades and surgical implants. Although in use for a number of years, Ti-6Al-4V alloy still attracts attention of researchers from both fundamental and practical points of view. [2].

The aim of this work is to analyze the effect of different quenching temperatures on the microstructure and mechanical properties of cast Ti-6Al-4V alloy. The alloy was characterized after heat treatment using microstructural investigation, tensile, charpy impact toughness and hardness tests. The fracture surface of the impact samples was investigated using Scanning Electron Microscope (SEM).

Experimental

The material used in this work was cast Ti-6Al-4V alloy. The chemical composition of the studied alloy is

given in Table 1.

TABLE 1 CHEMICAL COMPOSITION OF THE STUDIED ALLOY

Element	Al	V	Fe	C	O	N	H	Ti
wt. %	5.85	3.6	0.2	0.1	0.2	0.0016	0.005	Bal.

The samples were heated up to different temperatures in α+β range (900°C, 935°C, 980°C), then isothermally held for 10 minute, followed by water quenching. Programmable furnace with a controlled atmosphere was used for all heat treatment. The heat treatments were carried out in inert argon atmosphere at a flow rate of 200 CFH and 1 bar.

The as-cast and heat-treated specimens were prepared by standard metallographic techniques which consist of polishing and etching in an etchant composed of 10% HNO3, 5% HF, and 85% distilled water. After etching, the specimens were observed under optical microscope. X-ray diffraction with CuK_α radiation was used for phase analysis.

Tensile specimens according to ASTM E8 were machined using Electric Discharge Machining (EDM). Uniaxial tensile tests were carried out at room temperature at a strain rate of 0.5 mm/minute.

Standard Charpy V-notch impact specimens were prepared in accordance with ASTM E23 standard. Charpy impact tests were carried out using a 150-J capacity machine at room temperature. After impact testing, fracture surfaces of the notched specimens were carefully investigated by SEM to investigate the fracture mode and crack propagation behavior.

The average bulk Vickers hardness (Hv_{30}) of the specimens was measured. The applied load was 30 kg, loading time was 15 seconds and the speed of the indenter was 100 μm/second, according to ASTM E92. A surface layer, 3 mm thick, was removed by polishing to eliminate any oxidized layer prior to the hardness measurement.

Results and Discussion

Microstructural Investigation

Ti-6Al-4V alloy is characterized to be sensitive to microstructural variations. Many researches have been performed to obtain desired mechanical properties by controlling the microstructure through heat treatments. [9-13,15]. There are some commonly used heat treatments for the commercial Ti-6Al-4V alloy. Jovanovic et al. [2]. a typical procedure involves solutionizing at 100°C above T_β followed by quenching. However, other sources [1,9,15] suggest solutionizing below T_β which might be followed by aging. With these heat treatments, the tensile strength of Ti-6Al-4V alloy is increased by the transformation of β-phase to α' martensite phase on quenching and its decomposition to fine α and β-phases on aging. However, the above heat treatments have a problem that these take long time. It is reported [2,11,13] that these heat treatment cycles improve tensile strength but at the expense of ductility. In this work, the optimum solution treatment temperature for Ti-6Al-4V alloy is designed, where aim was to treat below T_β to avoid grain coarsening and formation of high fraction of brittle martensite without any subsequent aging to prevent the decomposition of retained β-phase to α and α' martensite to fine α and β-precipitates.

α to β transformation temperature for Ti-6Al-4V alloy used in this study was determined to be 987°C using heat-flux differential scanning calorimetry (DSC). This result is in agreement with pervious data. [1,14,15]. Pederson et al. [16]. reported that at all temperatures a significant proportion of the transformation has taken place during the time to hold at treatment temperature. At all temperatures, the phase fractions approach a constant value assumed to correspond to the equilibrium fraction. Pederson et al. [16]. also reported that α to β transformation is relatively fast at all temperatures, having occurred after 10 minute, and near-constant phase content being reached within 30 minute. From literature [1,2,9-13], the isothermal annealing time in α+β range is between 10 minute to one hour. In this work, 10 minute is selected for solution treatment in α+β range in order to avoid any grain growth of the cast structure. Water quenching was done for all heat treatment cycles.

Microstructure of the as-cast Ti-6Al-4V alloy is shown in FIG. 1. The bright regions correspond to α-phase, forming a typical Widmansttaten structure, whereas thin dark regions between α-plates are β-phase. In the Widmanstatten microstructure, α-phase is formed along prior β-grain boundaries; and colonies of lath-type β and α lamellar structure are present inside prior β-grains.

The microstructures after heat treatment are shown in FIG. 2. Water-quenching from these temperatures in α+β range leads to the formation of acicular α' martensite structure, of which volume fraction decreases with decreasing temperature, as reported by

many authors. [2,11,13]. The variation in solution treatment temperature produced a wider variation in volume fraction of primary α-phase. [2,4-6,12,14]. It is reported [2,12,4] that there is a continuous decrease in the amount of the acicular α' martensite relative to primary α-phase as the quenching temperature decreases. The presence of martensite in Ti-6Al-4V alloy has been widely reported. [1,2,4-6,12,13,15]. Martensite morphology cannot be detected using optical microscope. Imam et al [11] detected the morphology of the acicular α' martensite using Transmission Electron Microscope (TEM).

FIG. 1 MICROSTRUCTURE OF CAST Ti-6Al-4V ALLOY (200x)

β-phase appeared as thin dark areas between α-lamellae, in other word, β-phase appears as delimits of α-lamellae. These areas are likely to transform to martensite upon water quenching from high temperature in α+β range. Therefore, the formed martensite phase appears also as a thin dark layer surrounded by α-lamellae.

Optical micrographs of the alloy quenched from 900°C and 935°C are shown in FIG. 2-A and FIG. 2-B; respectively. As reported previously; [2,11,15] the microstructures formed in these conditions were a mixture of acicular α' martensite and β structures with α-plates formed inside and at prior β-grain boundaries. Primary α also begins to appear after quenching from α+β range. The microstructure quenched from 935°C, FIG. 2-B, has lower fraction of primary α-phase, in addition to that, the thin dark layers surrounding α-lamellae are thicker, compared to the microstructure quenched from 900°C as shown in FIG. 2-A. This reveals that the amount of martensite phase formed after quenching from 935°C is higher than that from 900°C.

The optical micrograph of the alloy quenched from 980°C and water quenched is shown in FIG. 2-C. Quenching from 980°C, just below T_{β}, results in a microstructure that consists nearly of acicular α' martensite with small volume fraction of α-phase. Morita et al. [13] reported that the retained β-phase may be located in the darkish area around the α'-phase.

These microstructural constituents are in agreement with the microstructure described by many workers [2,11,15] after heat treatment in α+β range followed by water quenching for Ti–6Al–4V alloy.

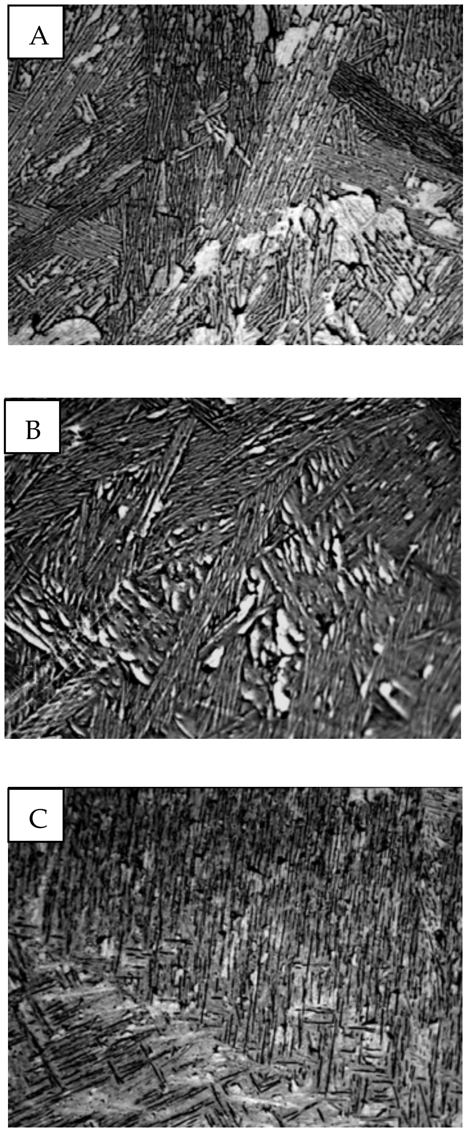

FIG. 2. OPTICAL MICROGRAPHS OF Ti-6Al-4V ALLOY QUENCHED FROM: (A) 900°C, (B) 935°C AND (C) 980°C. (200x)

Many authors [2,11,13] pointed out that the α-phase cannot be differentiated from α'-phase by X-ray diffraction measurements because the inter-planar spacing in the two structures is almost same. There by, the obtained X-ray diffraction data can only confirm the presence of a stable β-phase in quantities high

enough to be detected.

X-ray diffraction patterns of the as-cast sample and the sample quenched from 980°C are shown in FIG. 3. Diffractogram of the as-cast sample consists mainly of α-phase with small fraction of β-phase. The volume fraction of β-phase cannot be detected by XRD due to its low fraction and weak peak intensity. No traces of β-phase are visible in the pattern of the sample quenched from 980°C. The broadening of α reflections of the sample quenched from 980°C having the full width at half maximum (FWHM) is higher than that of the as-cast sample and is the evidence for the presence of the supersaturated α' martensitic phase with hcp structure. In addition to that the intensity of α'-reflections increases after quenching from 980°C indicating a high α' fractions. [2]. These results are in agreement in previous data. [2,11,13].

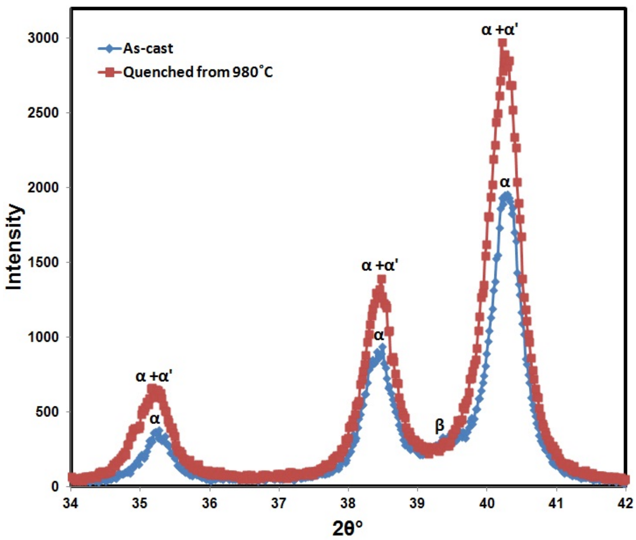

FIG. 3 X-RAY DIFFRACTION PATTERNS OF Ti-6Al-4V ALLOY.

Mechanical Tests

Solution treated and quenched metals are generally brittle immediately after a quench and hence tempering is necessary. Imam and Gilmore [11] reported that solution treatment and water quenching of the Ti-6Al-4V alloy does not necessarily produce a brittle metal, and it is possible that some useful properties may result from solution treated and quenched titanium alloys. However, very little work has been conducted on as-quenched titanium alloys. The data on values on hardness and mechanical properties of heat-treated Ti–6Al–4V alloy castings are rather limited. [2].

FIG. 4. shows the effect of quenching temperature on the tensile properties of Ti-6Al-4V cast alloy. As the solution temperature increases the tensile strength increase at the expense of tensile elongation. These results are in agreement with previous studies. [2,12,15]. This can be attributed to the increase in the amount of acicular α' martensite as the quenching temperature increases.

As expected, the hardest material corresponds to the lowest ductility. Similar results were obtained by Venkatesh et al. [15] who stated that the effect of α' and α was the major contributor for these trends and that the highest value of elongation corresponds to a discontinuity of the α-phase (in which slip can easily occur) because of the impediment of the β phase.

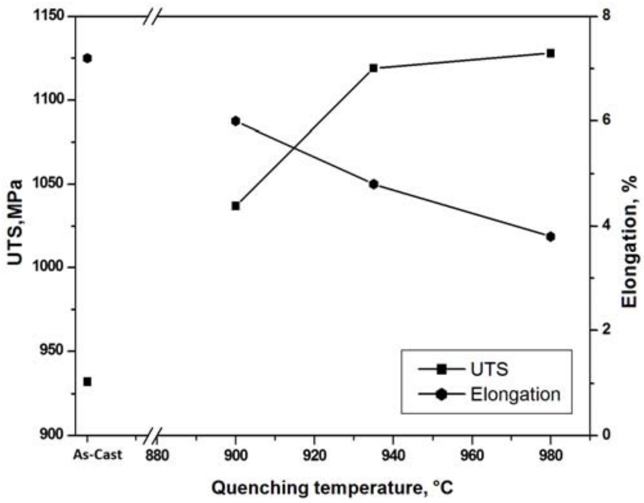

FIG. 4 EFFECT OF QUENCHING TEMPERATURES ON TENSILE STRENGTH AND ELONGATION

Hardness changes in the same manner with temperature as tensile strength. The change of hardness with solution treatment temperature is shown in FIG. 5. Quenching from 980°C exhibited much higher hardness values, while the as-cast specimen had the lowest hardness. In general, the hardness increases as the solution treatment temperature increases. This is due to the formation of α' martensite. These hardness results were in agreement with pervious results. [2,13,15].

FIG. 6. shows the effect of different quenching temperatures on Charpy impact toughness. As the quenching temperatures increases the Charpy impact toughness decrease. It is rational to obtain these results because it is in accordance with tensile elongation trend.

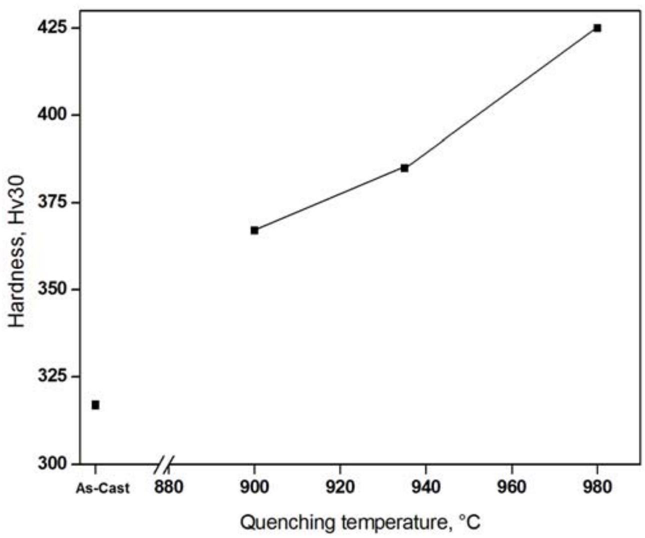

FIG. 5. CHANGE OF HARDNESS WITH QUENCHING TEMPERATURES

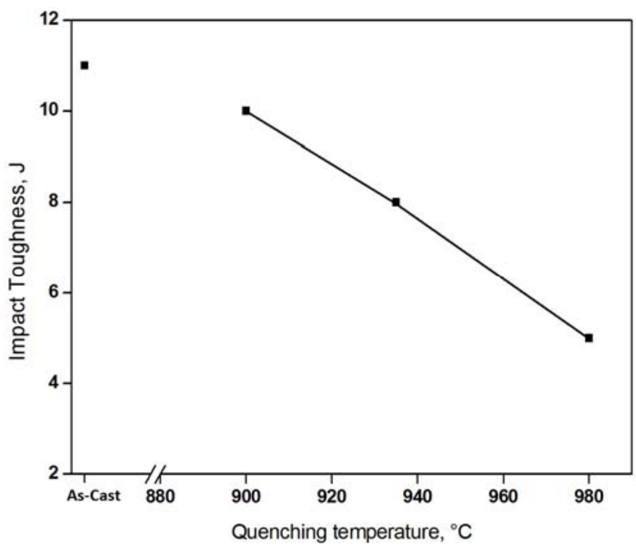

FIG. 6. EFFECT OF QUENCHING TEMPERATURES ON CHARPY IMPACT TOUGHNESS

To exemplify the influence of crack deflection and the material's ductility on the Charpy Impact behavior, SEM fractographs of the fractured samples are shown in FIG. 7. Fractographs of the as-cast microstructure show ductile fracture of dimple mode containing tiny cleavage type partly (FIG. 7-A). Large, tough α-plates of the as-cast alloy divert crack propagation paths and possibly reduce crack propagation by blunting the crack tip. Widmanstatten has large colonies of which lamellar structure consists of α-phase and strong β-phase, and these colonies have different lamellar direction. So crack branching and zigzaging are caused severely when cracks propagate, which increase resistance of crack propagation and bring out higher toughness.

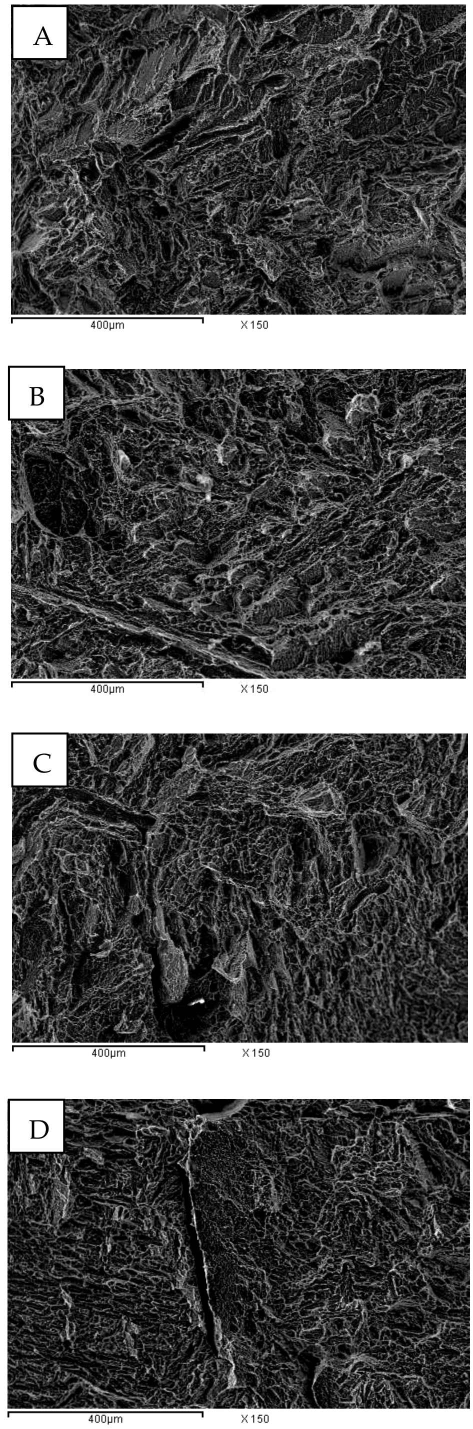

FIG. 7. FRACTURE SURFACE OF Ti-6A1-4V ALLOY: (A) CAST ALLOY, (B) QUENCHED FROM 900°C, (C) QUENCHED FROM 935°C AND (D) QUENCHED FROM 980°C.

As the quenching temperature increase the amount of dimples decrease. The conditions based on solution treated at 935°C and 900°C (FIG. 7-B and FIG. 7-C respectively) present less ductile fracture behavior, as they show pronounced shear lips and more dimples. The quenched microstructure from 980°C has a rough and smooth cleavage fracture surface and the increased cleavage size along with appearance of

cracks with different sizes, indicates a strong crack deflection, as shown in FIG. 7-D. This means that α' martensitic plates played a role of crack initiation sites and crack propagation, leading to clear cleavage fracture. Thin martensitic α' plates will provide a poorer medium for energy absorption and limit resistance to crack propagation. These mechanisms, of course, are directly related to the strength, ductility and toughness of the alloys. Morphology change of fractured surface before and after heat treatment is in accordance with decreasing aspect of impact toughness.

Conclusions

Mechanical properties of Ti-6Al-4V cast alloy are affected considerably by heat treatments and developed microstructures. Within the framework of this work, the tradeoffs in mechanical properties for different solution heat treatment temperatures have been analyzed. Tensile strength and hardness increase as the quenching temperature increases. On the other hand, tensile elongation and impact toughness decrease as the quenching temperature increases. This is attributed to the higher volume fraction of α' at higher quenching temperature.

The as-cast alloy exhibited a characteristic dimple-like ductile fracture with a large number of tear ridges. The fracture surface of the alloy quenched from 900°C consisted of dimples with some cleavage-like facets while the alloy quenched from 935°C has fracture surface similar to the fracture surface of the alloy quenched from 900°C with little amount of dimples. The fracture mode of the alloy quenched from 980°C exhibited more of cleavage cracking.

According to our results, a comproise between adequate values of strength and hardness from one side and elongation and impact toughness from other side can be achieved with adjusting the fractions of the different phases in the microstructure (α-, β-, α'-phase). This microstructure can be obtained by quenching from low temperature in α+β range, e.g. 900˚C.

ACKNOWLEDGMENT

This work was conducted and financially supported by Central Metallurgical Research and Development Institute (CMRDI)- Egypt.

REFERENCES

[1] L. W. Meyer, L. Krüger, K. Sommer, T. Halle and M. Hockauf. "Dynamic Strength and Failure Behavior of Titanium Alloy Ti-6Al-4V for a Variation of Heat Treatments" Mech Time-Depend Mater, Vol. 12, 237-247, (2008).

[2] M. T. Jovanovic, S. Tadic, S. Zec, Z. Miskovic and I. Bobic, "The Effect of Annealing Temperatures and Cooling Rates on Microstructure and Mechanical Properties of Investment Cast Ti-6Al-4V Alloy", Materials and Design, Vol. 27, 192–199, (2006).

[3] M. Bermingham, S. McDonald, M. Dargusch and D. StJohn, "Microstructure of Cast Titanium Alloys", Materials Forum, Vol. 31, 84-89, (2007).

[4] C. Leyens and M. Peters, "Titanium and Titanium Alloys, Fundamentals and Applications", WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, (2003).

[5] G. Lütjering and J. C. Williams, "Titanium", 2nd edition, Springer, (2007).

[6] ASM International, Titanium: A Technical Guide, American Society of Materials, Metal Park, Oh, (1988).

[7] R. Dąbrowski, "The Kinetics of Phase Transformations During Continuous Cooling of the Ti6Al4V Alloy from the Single-Phase β Range", Archives of Metallurgy and Materials, Vol. 56, Issue 3, 703-707, (2011).

[8] J. Stráský, M. Janecek, P. Harcuba, M. Bukovina and L. Wagner, "The effect of microstructure on fatigue performance of Ti-6Al-4V alloy after EDM surface treatment for application in orthopaedics", Journal of The Mechanical Behavior of Biomedical Materials, Vol. 4, 1955-1962, (2011).

[9] J. Cai, F. Li, T. Liu and B. Chen, "Investigation of mechanical behavior of quenched Ti-6Al-4V alloy by microindentation", Materials Characterization, Vol. 62, 287-293, (2011).

[10] D. G. Lee, S. Lee and Y. Lee, "Effect of Precipitates on Damping Capacity and Mechanical Properties of Ti–6Al–4V Alloy", Materials Science and Engineering, Vol. A, No. 486, 19-26, (2008).

[11] M. Imam and C. Gilmore, "Fatigue and Microstructural Properties of Quenched Ti-6AI-4V", Metallurgical Transactions, Vol. 14A, 233-240, (1983).

[12] C. Rhodes and N. Paton, "The Influence of α/β Interface Phase on Tensile Properties of Ti-6AI-4V", Metallurgical Transactions, Vol. 10A, 1753-1758, (1979).

[13] T. Morita, K. Hatsuoka, T. Iizuka and K. Kawasaki, "Strengthening of Ti-6Al-4V Alloy by Short-Time Duplex Heat Treatment", Materials Transactions, Vol. 46, No. 7, 1681-1686, (2005).

[14] R. Pederson, O. Babushkin, F. Skystedt and R. Warren, "The Use of High Temperature X-Ray Diffractometry to Study Phase Transitions in Ti-6Al-4V", in titanium alloys at elevated temperature: structure development and service behavior, institute of materials, ISSN 1336-5510, London, (2001).

[15] B. D. Venkatesh, D. L. Chen, S. D. Bhole, "Effect of Heat Treatment on Mechanical Properties of Ti–6Al–4V ELI Alloy", Materials Science and Engineering, Vol. A 506, 117-124, (2009).

[16] Winco K. C. Yung, B. Ralph, W. B. Lee and R. Fenn, "An Investigation Into Welding Parameters Affecting the Tensile Properties of Titanium Welds", Journal of Materials Processing Technology, Vol. 63, 759-764, (1997).

Reham Reda graduated from Faculty of Petroleum & Mining Engineering, Suez Canal University-Egypt, with a B.Sc. Eng. (Metallurgical and Materials Science Engineering) in 2006; she completed her M.Sc. in Metallurgical Engineering, Cairo University-Egypt in 2010. She is currently assistant researcher in Casting Technology Laboratory, Central Metallurgical Research and Development Institute (CMRDI)- Egypt.